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# Electrons in the VLHC Tunnels: The $e^+e^-$ and $ep$ Options

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We review the designs of a circular  $e^+e^-$  collider and a 1 TeV  $ep$  collider in the tunnels of the low field VLHC. Approximate parameters for an  $E_{cm} = 6.0$  TeV  $ep$  collider are also presented. These options could insure the diversity of the High Energy Physics program into the next century.

## I. MOTIVATION

If a 50 + 50 TeV hadron collider (VLHC) was constructed using superferric magnets with a field of about 2 T, the circumference would be roughly 530,000 m. In 1996 the parameters of a  $e^+e^-$  collider located in this tunnel were described. Since 1996, other data has determined that a Higgs is more likely at lower energies [5], and the energy range of 200 - 400 GeV in the center of mass may provide a significant fraction of the physics interest of any new lepton collider. While the maximum energy of a circular  $e^+e^-$  machine is not equal to that of the proposed linear collider, the cost should be much lower, the energy resolution would be better and the possibility of doing complementary physics would still exist. The required technology involved in circular colliders is comparatively conservative and operation of these devices is well understood. A circular lepton collider operating at energies above that of LEP could be a cost effective method of obtaining this data.

In 1998-1999 the option of a  $ep$  collider operating with the VLHC booster was considered. This design produces a center of mass energy of 1 TeV with useful luminosities. Both the  $e^+e^-$  [1] [2] and 1 TeV  $ep$  [3], [4] collider studies have been published. Assuming the electron ring from the  $e^+e^-$  collider is used with the VLHC ring, one can produce a  $ep$  collider with a center of mass energy of 6.0 TeV, and the rough parameters of this machine are given.

## II. COLLIDER DESIGNS

Any arbitrary limit on the synchrotron power that can be radiated by high energy electron beams limits the magnetic field in the arcs to low values and places a limit on the electron beam current, thus effectively limiting both the cost and performance of these rings. Since the synchrotron power rises as  $E^4$ , the limit on performance is fairly hard, and favors large, low field hadron machines. The ultimate question that must be decided is then whether the physics reach of such a machine is significant to justify an experimental program.

### A. $e^+e^-$ Collider

The basic parameters of such a machine operating at 180 GeV/beam, with a radiated power loss of 100 MW, are given in the following table [1].

TABLE I, Very Large  $e^+e^-$  Collider Parameters

Beam energy, $E$	180 GeV
Circumference, $C$	531 km
Luminosity, $L$	0.9 - 2.7 /nb/s
Center of mass energy spread, $\sigma_E$	0.26 GeV
Beam-beam tune shift, $\xi_x = \xi_y$	0.03 - 0.09
Particles / bunch, $n_e$	$80.4 \times 10^{10}$
Number of bunches, $k$	256
Synchrotron radiation power, $P$	50 MW/beam
Maximum dipole field, $B_{max}$	0.0083 T
Arc tune, $\nu_x \sim \nu_y$	258
RF voltage required	1.6 GV/turn

The larger beam-beam tune shifts seen in LEP at high energy [6] seem to offer the possibility of higher luminosities with this machine. These higher luminosities might be obtained by increasing the focusing in the arcs (decreasing  $\epsilon_x$ ), or with a smaller coupling constant  $\epsilon_y/\epsilon_x$ . Note that the center of mass energy spread is comparatively narrow (0.07 %). Since the energy for the maximum luminosity of a circular collider goes like  $E_{max} \sim R^{0.2}$ , there are diminishing returns involved in larger tunnels. Nevertheless if the tunnel parameters are determined by another machine such as the low field VLHC, the civil engineering can be fully utilized. Figure 1 shows the energy dependence of the luminosity compared with LEP [6] and the NLC [7].

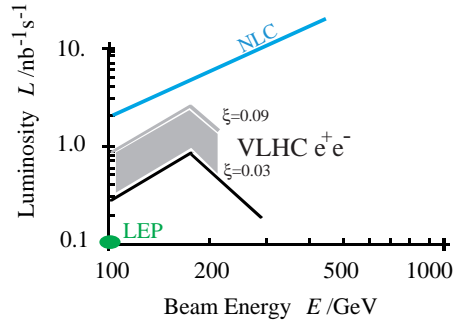


FIG. 1. The luminosity of a large  $e^+e^-$  collider compared with the NLC and LEP.

It seems desirable to use very long cell lengths in the collider since the tune is determined by the required equilibrium emittance, and using a small phase advance per cell with many cells produces a very small effective admittance, and limits the phase space volume over which the damping partition numbers are useful. In addition, the longer cell length is compatible with longer quadrupoles, which reduces the quadrupole gradient and the synchrotron radiation produced in quadrupoles. Although we have assumed pretzel orbits, the low magnet cost should permit the use of two rings if parasitic collisions are a problem.

Since the magnet aperture is determined by constraints on the interaction region quadrupoles and the maximum energy is constrained by the maximum radiated power, the basic parameters of the arc magnets are closely determined. Assuming the maximum field in the yoke is 0.8 T, the iron mass of the dipoles can be estimated at 24 kg/m or a total of  $1.1 \cdot 10^7$  kg. Assuming a cost of 2 - 3 \$/kg gives a magnet cost which would not contribute significantly to the total. The (50 MW) cooling and vacuum system and ( $\sim 20$  MW) power supplies should cost less than 1 \$/W since these systems are comparatively straightforward. The superconducting rf system is assumed to cost  $< 0.25$  \$/V.

## B. High and Very High Energy $ep$ Colliders

Two  $ep$  colliders are possible as part of the VLHC program. The parameters of a machine compatible with the present 3 TeV low field VLHC booster design, with the constraint that the synchrotron power would not exceed 50 MW is shown in Table II, together with some preliminary parameters for an  $ep$  collider which utilizes the Very Large high energy proton ring and  $e^+e^-$  collider ring.

TABLE II, Low and High Energy  $ep$  Collider Parameters

	Booster [3]	VL Ring
Electron beam energy, $E_e$	80	180 GeV
Proton beam energy, $E_p$	3000	50000 GeV
Circumference, $C$	34	531 km
Luminosity, $L$	0.26	0.14 /nb/s
Center of mass energy, $E_{cm}$	1	6.00 TeV
Number of bunches, $k$	340	6000
particles / bunch, $n_p, n_e$	12.5, 3.4	12.5, $10.1 \times 10^{10}$
Beam-beam tune shift, $\xi_{e,x}, \xi_{e,y}, \xi_{p,x}, \xi_{p,y}$	11, 21, 1.4, 6.8	$6.1, 2.9, 4.0, 0.3 \times 10^{-3}$
Synchrotron radiation power, $P$	50	50 MW
Maximum dipole field, $B_{max}$	0.083	0.008 T
RF voltage required	1.0	1.6 GV/turn

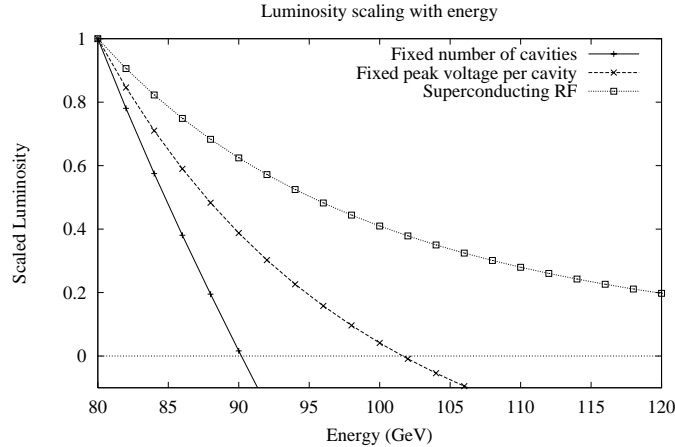


FIG. 2. The luminosity of the 1 TeV  $ep$  collider is determined by the rf system at high electron beam energies.

Figure 2 shows how the luminosity of the 1 TeV  $ep$  collider decreases with electron beam energy as a function of the rf system in the ring. This plot shows that compared with normal conducting rf, the use of superconducting rf extends the energy reach significantly and with a slower fall off in luminosity.

The higher center of mass energy would allow these machines to have a much larger kinematic reach in both  $Q^2$  and  $x$  than present data from HERA, as well as providing the opportunity for new physics. This would permit precision measurements of structure functions and other new physics which would complement the LHC and VLHC experimental programs.

The parameters for the high energy  $ep$  collider were obtained by assuming that the electron beam optics of the  $e^+e^-$  collider would be used, then increasing the number of electron bunches until the proton beam-beam tune shift is usefully small, keeping the total number of electrons in the ring constant. The interaction point parameters for the protons are adjusted to give the same beam sizes as are produced for electrons. While the number of electrons is constrained by the radiated power, the number of protons/bunch is determined by the injector chain and available technology.

The number of protons/bunch and beam emittance were estimated from preliminary booster design studies [8], and this number could theoretically be increased if high energy proton beams can be cooled using electron or stochastic cooling techniques. Since the electron beam-beam tune shift is comparatively low, the luminosity of the  $ep$  machines could be improved proportional to increases in the number of protons/bunch. Factors of 5 - 10 improvement are possible before the electron beam beam limits are reached. Although the total number of protons in the ring would still be less than that used in  $pp$  collisions, the limit on the number of protons per bunch is probably the transverse mode coupling, single bunch instability. This issue has received considerable study since Snowmass '96 [8].

If the high field version of the VLHC were used, one could have electron beam energies around 130 GeV and  $\sqrt{s} \sim 5$  TeV, with slightly lower luminosities than the 6 TeV option described here.

The fringe field of the proton ring produces large error fields which must be shielded since the injected electron beam energy is very low and the tunnel size limits the separation between the two rings. Although the removal of cooling water from the ring is comparatively straightforward, disposing of the resultant hot water without cooling towers may be challenging. In the booster the resultant hot water could be brought back to the Fermilab cooling ponds. For the large ring, we have been considering how the resulting 200 W/m could be disposed of locally.

### III. CONCLUSIONS

Large electron colliders operating in the tunnels of the VLHC could be a comparatively inexpensive way to insure the diversity of the high energy physics program in the LHC era. The design of large  $e^+e^-$  and  $ep$  collider rings is comparatively straightforward, however magnetic shielding of the electron rings where the relative momenta are very different ( $p_e/p_p = 0.026 \sim 0.0036$ ) and the removal of the synchrotron power from the tunnel in an environmentally neat way are concerns. While it is too early to cost any of these facilities, it seems likely that the costs of detectors, RF systems and collider rings might be roughly equal.

#### IV. ACKNOWLEDGMENTS

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